High Performance Capacitive Position Sensing Device for Compact Active Magnetic Bearing Spindles*

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High precision rotation of compact spindles that are contact-free suspended by active magnetic bearings, require high performance position sensors placed in suitable locations around the spindle. Industrial available position sensing devices either use large sensing probes, or are too expensive and are often already too application specific to be adapted. Therefore, an alternative position sensing device based on the electrostatic sensing principle measuring mutual capacitance is studied in this paper. For getting insight into the general tendency of mutual capacitance, an overview is elaborated by finite element modeling, mathematical derivations and experiments. It shows that there are three different types of spindle surface materials, each influencing the mutual capacitance in a different way. In addition, an optimized sensor pattern has been manufactured using a standard, low cost printed circuit board technology. First experimental results demonstrate a position measurement with a 40 [nm] resolution and a signal-to-noise ratio of 74 [dB].

Key Words: Sensor, Positioning, Measurement, Magnetic Bearing, Spindle

1. Introduction

Over the last couple of years, sensing devices have been miniaturized while retaining their outstanding performance. Additional developments have included higher efficiency due to new fabrication processes and through the introduction of digital signal processors and application specific integrated circuits. In parallel, it has been appreciated that it is difficult to achieve stringent performance goals in a controlled system, without including the sensor properties into the design and integration face. This has resulted in an increased demand for high quality sensors and actuators chosen specifically for the application at hand.

One of such applications, which is used in this paper as a benchmark application, is the development of compact, high precision spindles suspended by

active magnetic bearings. An active magnetic bearing system is composed of position sensors, a controller, amplifiers and electromagnetic actuators^{(1),(2)}. High precision rotation can be achieved by improving the controller as well as by placing high performance position sensors in suitable locations around the spindle⁽³⁾⁻⁽⁵⁾.

A comparative review of performance characteristics, operating principles and application specific demands, has offered insight into the state-of-the-art of contact-free position sensing devices. It showed that industrial available position sensing devices either use large sensing probes, or are too expensive and are often already too application specific to be adapted⁽⁶⁾. In addition, when severe boundary conditions are demanded, widely used eddy current sensors are too noisy to obtain a high resolution and optical reflection sensors encounter an inevitable high sensitivity to surface irregularities. Therefore, an alternative position sensing device based on the electrostatic sensing principle is studied in this paper.

2. Nomenclature

a, b : constants that shape trendline

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- c : constant $c (= \epsilon S_e/2)$
 C : capacitance
 C_{AB} : capacitance between electrodes A and B
 C_{AT} : capacitance between electrode A and spindle surface T
 C_{BT} : capacitance between electrode B and spindle surface T
 $C_{m,d}$: mutual capacitance for dielectric spindle surface material
 $C_{m,f}$: mutual capacitance for floating spindle surface
 $C_{m,g}$: mutual capacitance for grounded spindle surface
 $C_{m,nom}$: nominal mutual capacitance
 C_p : parallel-plate capacitance
 C_{par} : parasitic capacitance
 $C_{p,tot}$: total parallel-plate capacitance
 ϵ : dielectric constant
 ϵ_0 : dielectric constant of vacuum
 ϵ_r : relative dielectric constant
 $\epsilon_{r,eff}$: effective, relative dielectric constant
 E_r : relative electric field intensity
 h : electrode height
 L : electrode length
 N : number of electrode pairs
 p : electrode pitch
 Q_A : total amount of surface charge induced on electrode A
 Q_B : total amount of surface charge induced on electrode B
 Q_{AB} : amount of surface charge induced on electrode A or B due to Q_{AB}
 $Q_{T,left}$: total amount of surface charge induced on left side of spindle surface T
 $Q_{T,right}$: total amount of surface charge induced on right side of spindle surface T
 S_e : area of electrode surface
 S_s : area of sensor surface
 t : thickness of printed circuit board
 ΔV_{AB} : potential difference between electrode A and B
 w : electrode width
 x : distance between electrodes and spindle surface
 x_{min} : distance where mutual capacitance is minimum

3. Electrostatic Sensing

The electrostatic sensing principle is based on changes in the energy stored in an electric field. Sensors using this principle can be represented by capacitive elements. These consist of two electric conductors separated by a dielectric (solid, liquid or gas) or by a vacuum. The capacitance C is then a

Fig. 1 Capacitive sensor configurations

function of the geometrical arrangement of the conductors and on the dielectric medium between them.

3.1 Co-planar configuration

A commonly used configuration consists of two parallel-placed electrodes A and B facing each other. In this so-called co-planar configuration, the spindle surface represents one of the electrodes, as is visualized in Fig. 1(a). The capacitance C_p between the two electrodes can be written as:

$$C_p = \frac{\epsilon S_e}{x} \quad (1)$$

where ϵ is the dielectric constant, S_e is the area of each electrode surface and x is the distance between the two electrodes. Since the spindle is contact-free suspended as well as rotating, no connection can be made with it. Therefore, this configuration cannot be used in the benchmark application foreseen.

3.2 Uni-planar configuration

Figure 1(b) shows an uni-planar configuration where two electrodes A and B are placed on a single substrate and the spindle surface T represents a third counter plate. A potential difference between the two electrodes will generate a fringe field that creates a mutual capacitance between the two conductors. Since the proximity of the spindle surface will change the fringe field, a change in the mutual capacitance can be used to measure the position of the spindle.

4. Modeling Mutual Capacitance

A literature research revealed several analytical and numerical approximations about calculating mutual capacitances. These give reasonable estimates of the mutual capacitance per unit length between nearby conductors^{(7)–(10)}. Nevertheless, no comprehensive overview was found for getting insight into the general tendency of mutual capacitance. Therefore, in the first step towards such a representation, a model of the nominal mutual capacitance has been studied.

4.1 Nominal value

The nominal mutual capacitance $C_{m,nom}$ is the capacitance between two electrodes placed adjacent

to each other without the proximity of the spindle surface. The electrodes are modeled by two conductors, each with a length L , a width w and a height h . Moreover, both conductors are placed with a pitch p between each other on a single substrate as shown in Fig. 2. The model of Walker⁽¹¹⁾ approximates the nominal mutual capacitance $C_{m,nom}$ per unit length L by ($p > w$):

$$\frac{C_{m,nom}}{L} \approx \frac{\pi \epsilon_{r,eff} \epsilon_0}{\ln \left(\frac{\pi(p-w)}{w+h} + 1 \right)} \quad (2)$$

where $\epsilon_{r,eff}$ is the effective relative dielectric constant and ϵ_0 is the dielectric constant of vacuum.

4.2 Influence of spindle surface type

A next step for modeling mutual capacitance includes the proximity of the spindle. There are three different spindle surface materials, each of them influencing the mutual capacitance in a different way⁽¹²⁾

In the first case, the proximity of a conductive and grounded spindle surface (i.e. connected to ground) will act as a third, parallel-placed counter electrode. It will create an additional parallel-plate capacitance from each electrode to this spindle surface T and these capacitances C_{AT} and C_{BT} will increase with decreasing distance. However, as is illustrated by the schematic of the electric equivalent in Fig. 3, their change is not being measured when measuring the capacitance between the electrodes A and B . Still, C_{AB} is being influenced by the approach of a grounded spindle surface and this has been simulated by the finite element program Femlab[®]. This program permits to calculate and visualize electric field intensities E between conductors. Figure 4 shows the 2D-model that has been used for the simulation, assuming the spindle as a plane. Two electrodes, A and B , have been designed adjacent to each other on a substrate

Fig. 2 Model of Walker

Fig. 3 Schematic of electric equivalent of grounded spindle surface

with a certain thickness, assuming that no fringe field lines will cross the lower border side of this substrate. Moreover, the grounded spindle surface has been modeled as two parts, *left* and *right*, each sufficiently wide to avoid any side effects. The simulation results for two distances of x are visualized in Fig. 5. These show that the relative electric field intensity E_r between the electrodes decreases when a grounded spindle surface comes closer. Due to the so-called shielding effect, more and more fringe field lines will rather terminate on the spindle surface, than cross to the neighboring electrode⁽¹¹⁾. Therefore, the amount of charge Q_{AB} that is induced on one of the electrodes A or B due to their potential difference ΔV_{AB} , decreases with the proximity of a grounded spindle surface. Hence, the mutual capacitance $C_{m,g}$ decreases as well since:

$$C_{m,g} = C_{AB} = \frac{Q_{AB}}{\Delta V_{AB}} \quad (3)$$

The electric field intensities E at several distances of

Fig. 4 2D-model for simulation of proximity of grounded spindle surface

Fig. 5 Simulation result of approach of grounded spindle surface where E_r is a relative value

x have been used to determine Q_{AB} . According to Gauss' law, the total surface charge Q on each electrode (Q_A and Q_B) and on the *left* and *right* part of the spindle surface T ($Q_{T, left}$ and $Q_{T, right}$) can be calculated by:

$$Q = \oint_S \epsilon E dS \quad (4)$$

Because a 2D-model is considered here, the surface S reduces to a continuous path around the conductors. The surface charge Q_{AB} is then obtained by using the following equation:

$$Q_{AB} = |Q_A| - |Q_{T, left}| = |Q_B| - |Q_{T, right}| \quad (5)$$

Figure 6 shows the values of the mutual capacitance $C_{m,g}$ that have been calculated using Eqs.(3), (4) and (5). These values have been mathematically fit by a trend line, such that $C_{m,g}(x)$ for $1 < x < 400$ [μm] can be described by:

$$C_{m,g}(x) \cong a \ln(x) + b \quad (6)$$

where a and b are constants that shape the trend line.

In the second case, the proximity of a conductive and electrically floating spindle surface (i.e. not connected to ground) will create a parallel-plate capacitance from each electrode to the spindle surface as well. This is illustrated by the schematic of the electric equivalent in Fig. 7. The parasitic capacitance C_{par} is not included into the model, because it does not influence the mutual capacitance. Now, a change in the parallel-plate capacitance from each electrode to the spindle surface is being measured when measuring the capacitance C_{AB} between the electrodes A and B. This implies that for describing the influence of the proximity of a floating spindle

Fig. 6 Simulation result and trend line of mutual capacitance versus distance to grounded spindle surface

Fig. 7 Schematic of electric equivalent of conductive and electrically floating spindle surface

surface, the shielding effect of a grounded spindle surface can be seen coupled with a parallel-plate effect. For the latter one, the total parallel-plate capacitance $C_{p,tot}(x)$ is given by:

$$C_{p,tot}(x) = \frac{1}{\frac{1}{C_{AT}(x)} + \frac{1}{C_{BT}(x)}} \cong \frac{\epsilon S_e}{2x} = \frac{c}{x} \quad (7)$$

where c a constant, with $c = \epsilon S_e/2$. Combining Eq. (6) with Eq.(7) provides an approximation for the mutual capacitance $C_{m,f}(x)$ of a floating spindle surface and yields for $x > 0$:

$$C_{m,f}(x) \cong C_{m,g}(x) + C_{p,tot}(x) \cong a \ln(x) + b + \frac{c}{x} \quad (8)$$

The influence of the proximity of a floating spindle surface is shown in Fig. 8. As can be seen, the approach of a floating spindle surface will first decrease the mutual capacitance $C_{m,f}(x)$ to a certain minimum with decreasing distance x and then it will increase again with a further decrease in the distance x .

In the third case, that can influence the mutual capacitance, the spindle surface material is a dielectric (i.e. non-conductive). Now, the original dielectric medium, e.g. air, is essentially being replaced by the spindle surface material that has a higher relative electric permittivity ϵ_r . Therefore, additional charge may be stored in this dielectric medium. This is reflected as an increase in the mutual capacitance between the electrodes as function of the distance x to the spindle.

Table 1 illustrates the specific influence of the proximity of the three different types of spindle surface materials on the mutual capacitance between two electrodes A and B. As already mentioned before, the spindle is contact-free suspended as well as rotating. Therefore, only a conductive and floating spindle surface will be taken into account for further examination.

4.3 Geometrical parameters

The change in the mutual capacitance due to a

Fig. 8 Trend of influence of proximity of electrically floating spindle surface

Table 1 Overview of the specific influence the proximity of three different kinds of target types has on the mutual capacitance between two electrodes A and B. Each configuration can be represented by a simplified electric equivalent schematic.

dielectric	conductive	
	grounded	floating

spindle displacement (i.e. sensitivity) is approximated by taking the derivative of Eq. (8) and yields for $x > 0$:

$$\frac{dC_{m,f}(x)}{dx} \approx \frac{a}{x} - \frac{c}{x^2} \quad (9)$$

Equation (9) indicates that there exists a certain distance $x_{\min}$ where the sensitivity is equal to zero. This means that for distances smaller than $x_{\min}$, the constant c is mostly responsible for the sensitivity achievable and a change in the mutual capacitance is generally caused by a parallel-plate effect. Here, an increase of the area of electrode surface S_e (i.e. L and w) will contribute to a higher sensitivity. For distances greater than $x_{\min}$, the constant a is mostly responsible for the sensitivity achievable and a change in the mutual capacitance is generally caused by a shielding effect. The constant a sets the slope of the trend line such as the one shown in Fig. 6. A steeper slope means that for great distances between the spindle surface and the electrodes, the mutual capacitance will be higher than for a less steeper slope. If assumed that at great distances the mutual capacitance corresponds to the nominal mutual capacitance $C_{m,nom}$, then the constant a can be expressed by the geometrical parameters used in Eq. (2). Therefore, the constant a is proportional to the electrode length L and to the electrode width w and inversely proportional to the pitch p between the electrodes. Hence, for distances greater than $x_{\min}$ the sensitivity can be increased by increasing L and w or by decreasing p . Figure 9 illustrates the two different areas with their most prominent effect on the mutual capacitance and also indicates the operation range.

Fig. 9 Trend of normalized mutual capacitance versus distance to electrically floating spindle surface

Fig. 10 Comb-shaped pattern for a given area of sensor surface S_s

The above mentioned findings point out the direction for the design of a sensor pattern that maximizes the sensitivity. This can be achieved by a so-called comb-shaped pattern, as is illustrated in Fig. 10. For a given area of sensor surface S_s , it contains N pairs of two electrodes, each with a width w and length L , placed adjacent to each other with a pitch p .

5. Signal Conditioning

There are many measurement methods to choose from when measuring a change in capacitance. Common methods can be divided into capacitive bridge, resonance and charge-discharge methods. Two measurement systems that were available in the laboratory have been used to measure the mutual capacitance of the sensor patterns designed. The HP 4263A LCR-meter uses an auto-balancing bridge section to measure the mutual capacitance value directly in Farads. An oscillator inside the Senstech 6250 capacitance meter drives the electrodes with an AM-signal that has a frequency of 62.5 [kHz]. The amplitude of this signal is being altered by a change in capacitance and after a synchronous rectification an analog output signal proportional to the mutual capacitance is obtained.

6. Experimental Results

For the model verification, capacitive sensing electrodes with a comb-shaped pattern and a given

sensor size S_s of 5×10 [mm²] were printed on printed circuit boards (PCBs). The PCB manufacturing allowed a minimum electrode width w of 100 [μ m] and a minimum pitch p of 200 [μ m]. Therefore, these geometrical parameters have been altered according to $w \in \{100; 200; 300\}$ [μ m] and $p \in \{200; 300; 400\}$ [μ m]. Furthermore, the thickness t of the PCBs was set to 0.12 [mm] and 1.6 [mm]. The former allowing flexible sensing electrodes. Finally, the conductor height h was also determined by the PCB manufacturing and was set to 35 [μ m].

6.1 Nominal mutual capacitance

The nominal mutual capacitance of the different sensing electrodes has been calculated using the model of Walker and was measured using the LCR-meter. A comparison of the results obtained is given in Table 2. The model of Walker shows a good correspondence. It proves to be an accurate model for predicting the nominal mutual capacitance. In addition, the influence of the thickness of the PCB can be observed. The nominal mutual capacitance for the 0.12 [mm] PCB is slightly lower than for the 1.6 [mm] PCB. Since the electrodes are very thin and tightly placed next to each other, the penetration depth into the PCB (ϵ_r of about 4.5 [-]) is rather low. Therefore, even for a thickness of 0.12 [mm], most flux lines will not cross beyond the PCB. Finally, increasing the electrode width w and pitch p between the electrodes will reduce the amount of electrode pairs N on a given area of sensor surface S_s . Hence, the nominal mutual capacitance decreases as is indicated.

6.2 Conductive and electrically floating spindle surface

For testing the influence of the proximity of a conductive and electrically floating spindle surface, a PCB with a specific comb-shaped sensing pattern was attached to a fixed support. The spindle could be moved towards the PCB. The LCR-meter was used to measure the change in the mutual capacitance. A measurement result for a specific comb-shaped pattern ($w01p02t1.6$) is shown in Fig. 11. For large distances it is clearly visible that the influence of a floating spindle surface corresponds very well to that of a grounded spindle surface, as was predicted by the model for a floating spindle surface. Moreover, the distance where the mutual capacitance has a minimum is present and the behavior below this distance corresponds to the prediction of the model as well.

6.3 Sensor patterns

Several measurements were carried out to verify the maximum sensitivity achievable for different geometrical parameters. In Fig. 12 a result is shown for two different comb-shaped patterns. The capaci-

Table 2 Measured and calculated values for the nominal mutual capacitance of the different sensing electrodes

pattern dimensions	measured	Walker	
	value [pF]	value [pF]	error [%]
w01 p02 t1.6 ^a	10.41	10.66	+2.4
w02 p04 t1.6	5.45	5.12	-6.2
w01 p02 t0.12	9.33	9.38	+0.6
w02 p04 t0.12	4.72	4.52	-4.2

a. width $w01=100$ [μ m], pitch $p02=200$ [μ m] and thickness $t1.6=1.6$ [mm]

Fig. 11 Experimental result for a specific comb-shaped pattern

Fig. 12 Mutual capacitance versus displacement for comb-shaped sensor patterns with different geometrical parameters

tance values measured have been re-scaled, so that the sensitivity can be easily compared. As can be seen, an increase in the pitch p between the electrodes is proportional to a decrease in the sensitivity (i.e. less steep slope).

More interesting is to see that the distance $x_{\min}$ of the minimum value of the mutual capacitance (i.e. sensitivity equal to zero) hardly moves when the pitch p is altered. This can be explained by solving Eq. (9)

for a sensitivity equal to zero and yields:

$$\frac{dC_{m,f}(x_{\min})}{dx} = 0 \rightarrow x_{\min} \cong \frac{c}{a} \quad (10)$$

Hence, the distance $x_{\min}$ is proportional to the constant c and inversely proportional to the constant a . Since the pitch p is inversely proportional to the constant a , an increase of p results in a decrease of the constant a . Moreover, because the area of sensor surface S_s is kept fixed, an increase of the pitch p will decrease the amount of electrode pairs N . Consequently, the overall area of electrode surface S_e will decrease and since the constant c is proportional to S_e , it will decrease as well. Therefore, both the constants a and c will decrease when the pitch p is increased and the location of $x_{\min}$ will hardly be influenced.

6.4 Sensing device performance

A maximum sensitivity of 6 [fF]/[μm] was obtained by using the comb-shaped pattern with the geometrical properties $w0.1p0.2t1.6$. Since for this pattern $x_{\min}$ is located at 30 [μm], the operation range was set from 100 [μm] to 300 [μm]. Two of these sensing patterns were placed in a differential set up, facing an electrically floating spindle surface at a stand-off distance set to 0.1 [mm]. This is visualized in Fig. 14. The spindle could be moved by steps of 100 [nm] using a stepping motor. The capacitance meter was used to convert the change in mutual capacitance into a DC-voltage. Moreover, its low pass filter was set at a cut-off frequency of 2.5 [kHz]. Figure 13 shows a diagram of the response of the position sensing device to a spindle displacement.

In addition, an oscilloscope was used to analyze the noise level of the output signal. As can be seen in Fig. 15, the noise can be fit by a Gaussian probability density function with a low standard deviation, resulting in a high resolution measurement. The main characteristics of the position sensing device designed have been summarized in Table 3. The S/N-ratio has been calculated by taking into account the full scale output voltage and the noise level of the position sensing device.

7. Conclusion

A position sensing device based on the electrostatic sensing principle measuring mutual capacitance has been studied. For getting insight into the general tendency of mutual capacitance, an overview was elaborated by finite element modeling, mathematical derivations and experiments. It showed that there are three different types of spindle surface materials, each influencing the mutual capacitance in a different way. Of special interest was the investigation of an electrically floating (i.e. not grounded) spindle surface. It

Table 3 Main characteristics of the capacitive sensing device

property	value	unit
operation range ^a	0 to 200	[μm]
sensitivity	50	[mV/ μm]
resolution	40	[nm]
S/N-ratio	74	[dB]

a. stand-off distance equal to 0.1 [mm]

Fig. 13 Picture of the experimental set-up

Fig. 14 Output signal of capacitive position sensing device versus displacement

Fig. 15 Noise amplitude probability distribution with a Gaussian curve fit

was shown that the effect of the proximity of such a spindle surface can be seen as a combination of a shielding effect and a parallel-plate effect. Moreover, a mathematical model as well as experimental results revealed the existence of a minimum in the mutual capacitance as function of the distance x between the sensing electrodes and the spindle surface.

An optimized sensor pattern was manufactured using a standard, low cost PCB technology. First experimental results demonstrated a position measurement with a 40 [nm] resolution and a signal-to-noise ratio of 74 [dB]. It has to be mentioned that a standard laboratory capacitance meter was used to conduct the measurements. All in all, using the principle of mutual capacitance for position sensing features flexibility on sensor size and sensing patterns. Besides, since all sensing electrodes can be created on one single substrate, the accuracy of the capacitances depends on that of the manufacturing process, rather than on the positioning accuracy for parallel-plate configurations. In addition, using large electrodes curved around the spindle will have a spatial averaging on surface irregularities as well. Finally, for distances greater than $x_{\min}$, only the presence of the spindle surface and not its potential contributes to the capacitance between the electrodes. Hence, no active shielding is required, which is common in case of a parallel-plate configuration.

The experimental setup has not been further developed for integration into the benchmark application. Therefore, research still has to be carried out in order to demonstrate the findings described above.

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